# Hyperfine structure and isotope shift of $^{82}$Rb $D_1$ and $D_2$ transitions

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We report on the hyperfine-structure measurements of the $5P_{1/2}$ and $5P_{3/2}$ states as well as the isotope shift of the $D_1$ transition of radioactive $^{82}$Rb ($t_{1/2} = 75$ s) atoms trapped in a magneto-optical trap. The systematic effects of light shift (ac Stark shift) and power broadening were explored to verify the accuracy of our trap and probe method against saturation spectroscopy results in $^{85}$Rb. The hyperfine-splitting magnetic-dipole coefficient ($A$) for the $^{82}$Rb $5P_{1/2}$ state and the isotope shift of the $D_1$ transition ($\delta\nu^{82-85}$) was measured to be 122.7(1.0) MHz and $-150.8(2.0)$ MHz, respectively. The hyperfine splitting for the $^{82}$Rb $5P_{3/2}$ state was determined to be 90.3(1.5) MHz in agreement with the previous measurement of 89.3(9.0) MHz [C. Thibault *et al.*, Phys. Rev. C **23**, 2720 (1981)]. These measurements provide key information that is needed to manipulate and determine the polarization of trapped $^{82}$Rb atoms for a parity violating $\beta$-asymmetry measurement. [S1050-2947(99)01012-4]

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## I. INTRODUCTION

Since the demonstration of magneto-optical trapping [1] of neutral atoms, there has been a growing interest in exploiting this technology in atomic and nuclear physics. Trapped $\beta$-decaying species will enable a new set of high precision measurements that will further elucidate the helicity structure of the electroweak interaction and aid in the search of physics beyond the standard model. In many ways, trapped radioactive atoms make an ideal source for $\beta$-decay correlation measurements since relatively intense sources can be harnessed which are effectively massless, pointlike, and nearly 100% spin polarized. Consequently, systematic effects associated with electron scattering and polarization uncertainty can be greatly reduced if not eliminated altogether. With the recent success in trapping large numbers ($\sim 10^6$) of radioactive $^{82}$Rb ($t_{1/2} = 75$ s) atoms [2,3], a new set of fundamental symmetry $\beta$-decay correlation experiments with $^{82}$Rb are now possible.

To undertake these precise electroweak interaction measurements, information on the atomic structure of $^{82}$Rb is needed. In particular, we intend to polarize $^{82}$Rb atoms by optically pumping them into the $5S_{1/2}, F = 3/2, m_F = 3/2$ weak field seeking state and then confining them to a time-averaged orbiting potential magnetic trap which will serve as a rotating beacon of spin-polarized nuclei. Since either the $D_1$ or $D_2$ transition could be used in the optical pumping or $m$-state population measurement of polarization, detailed knowledge of these transitions is required. Up to this time, only the $D_2$ line hyperfine structure and isotope shift for $^{82}$Rb has been reported [4].

In this paper we present a first time measurement of the hyperfine structure in the $5P_{1/2}$ state and the isotope shift of the $D_1$ transition, as well as an improved measurement of the hyperfine splitting of the $5P_{3/2}$ state in radioactive $^{82}$Rb atoms confined to a magneto-optical trap (MOT). Since atoms in a MOT are intrinsically perturbed by the trapping light and magnetic field, systematics such as the light shift and Zeeman shift have been minimized and/or corrected to give accurate results.

## II. EXPERIMENT

The experiment was performed using $^{82}$Rb atoms confined in a magneto-optical trap. The system setup and method for trapping $^{82}$Rb has been reported earlier [2,3]. Briefly, a chemically concentrated and purified sample is placed in an ion source of a mass separator. Rb is selectively ionized, electrostatically extracted at 20 kV and passed through a mass separator where a single mass line is selected, refocused with an electrostatic quadrapole triplet, and implanted into a small catcher foil located inside a trapping cell. The catcher foil is inductively heated to release the implanted Rb species as neutral atoms into a dryfilm-coated quartz cell where they are trapped by a MOT. The magneto-optical trap is formed by three retroreflected, circularly polarized laser beams (50 mm $1/e^2$ width) which enter the 75-mm cubic cell through each surface. A set of anti-Helmholtz coils generate the quadrupole field gradient of 7 G/cm in the axial direction. A Ti:sapphire laser tuned to the $D_2$ line of Rb at 780 nm forms the trapping beams. The relevant $^{82}$Rb energy levels and atomic transitions are shown in Fig. 1. The laser frequency is locked 15 MHz below the $5S_{1/2}, F = 3 \rightarrow 5P_{3/2}, F' = 4$ trapping transition in $^{85}$Rb using a frequency-modulated (FM) sideband technique [5]. A double-pass acoustic-optical modulator (AOM) driven at 268 MHz provides the 536-MHz frequency shift needed to excite the $5S_{1/2}, F = 3/2 \rightarrow 5P_{3/2}, F' = 5/2$ trapping transition in $^{82}$Rb. In order to repump atoms which fall into the $5S_{1/2}, F = 1/2$ ground state, sidebands are added to the trapping beam by using an electro-optical modulator (EOM) tuned to 1.470 GHz which excites the $5S_{1/2}, F = 1/2 \rightarrow 5P_{3/2}, F' = 3/2$ transition. A probe beam is retroreflected and overlapped with the trapped atoms. The fluorescence signal from the trapped atoms is modulated by the modulating probe beam and imaged onto a photomultiplier. The trapping signal is then demodulated using a lock-in amplifier to reject
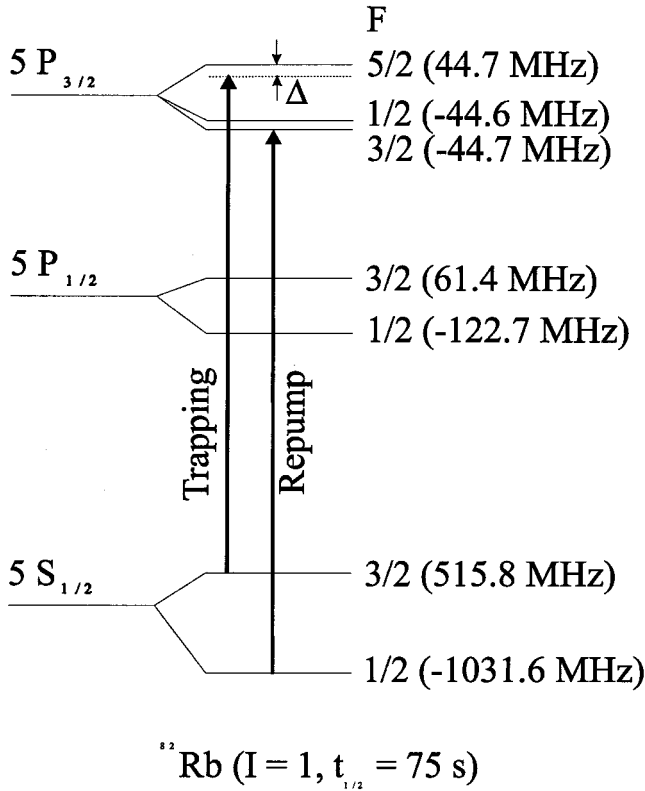
F

5 P$_{3/2}$   5/2 (44.7 MHz)
            1/2 (-44.6 MHz)
            3/2 (-44.7 MHz)

5 P$_{1/2}$   3/2 (61.4 MHz)
            1/2 (-122.7 MHz)

Trapping   Repump

5 S$_{1/2}$   3/2 (515.8 MHz)

            1/2 (-1031.6 MHz)

$^{82}$Rb (I = 1, t$_{1/2}$ = 75 s)

FIG. 1. The lowest three energy levels of $^{82}$Rb (not to scale). The hyperfine splittings given in parentheses are the results reported herein and those of Ref. [4]. The trapping (detuned by $\Delta$) and repump transitions used to trap atoms in the magneto-optical trap are also shown.

the laser scattered background.

A major change of the experimental setup from Refs. [2,3] is the addition of a Ti:sapphire probe laser. This probe laser is locked to the $^{85}$Rb saturation lines using the same FM sideband technique mentioned above. The power of the probe beam is kept low ($<100$ $\mu$W/cm$^2$) to avoid any probe beam light shift as well as probe and trapping light multiphoton effects. In the weak probe light limit, it is well known that a strong pump field (trapping light field) gives rise to an ac Stark splitting, also known as Autler-Townes splitting, when probing via a third level [6,7]. For a large detuned field, one of the dynamic Stark (single photon) components will only be slightly shifted from the two-level transition frequency, while the other (two-photon) resonance will have a negligible intensity. Under this condition, the effect of the pump field is to produce a quadratic ac ($\propto E^2$) Stark shift and can be understood with second-order perturbation theory. We minimized this shift by measuring the light shift at different laser trapping intensities and then extrapolating the light intensity to zero. The net effect of a small dc magnetic field in a MOT is to broaden the $D_1$ and $D_2$ lines due to the symmetric splitting of these levels into magnetic substates which could not be resolved in these measurements. To minimize this broadening effect, judicious care was taken to balance the trap so that the center of the trap cloud coincides with the center of the quadrupole field where the magnetic field is zero. This was essential in obtaining a reproducible light shift.
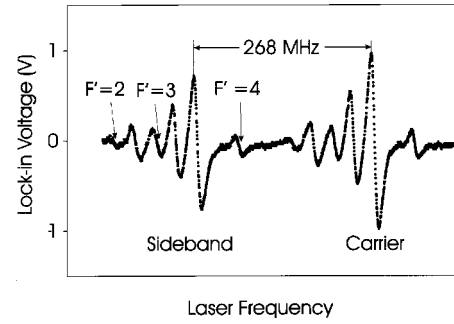


FIG. 2. Laser frequency scan through the FM saturation absorption signal of the $^{85}$Rb $D_2$ line $F=3 \rightarrow F'=2,3,4$ transitions and their associated crossover peaks using a rubidium vapor cell. The two sets of identical peaks were generated by the carrier and sideband of an AOM modulator operating at a frequency of 268 MHz.

## III. RESULTS AND DISCUSSION

### A. Frequency references

Saturated absorption spectroscopy using Rb vapor cells provides our frequency reference. Here intensities of the probe and pump beams of the saturation absorption are kept low ($<1$ mW/cm$^2$) to avoid any light shift. The accuracy of the frequency-locking method was checked (see Fig. 2) with the well-known hyperfine structure of $^{85}$Rb [8] and a repeatable accuracy of 0.5 MHz was achieved when care was taken to adjust the zero offset of the differential error signal.

### B. $D_1$ transition

For the $D_1$ line ($5S_{1/2} \rightarrow 5P_{1/2}$) measurement, the probe beam is derived from the probe laser and its frequency is shifted with a wide-band EOM. The probe beam frequency is modulated in and out of resonance with the $^{82}$Rb $D_1$ transition to produce a modulation on the fluorescence signal of the trapped atoms. Because the probe beam has a depumping effect on the trapped atoms, the repump intensity of the trap is kept to a minimum in order to maximize this effect. We first tested the accuracy of our method on the $^{85}$Rb $D_1$ line. For this measurement, the probe laser is locked to the cross-
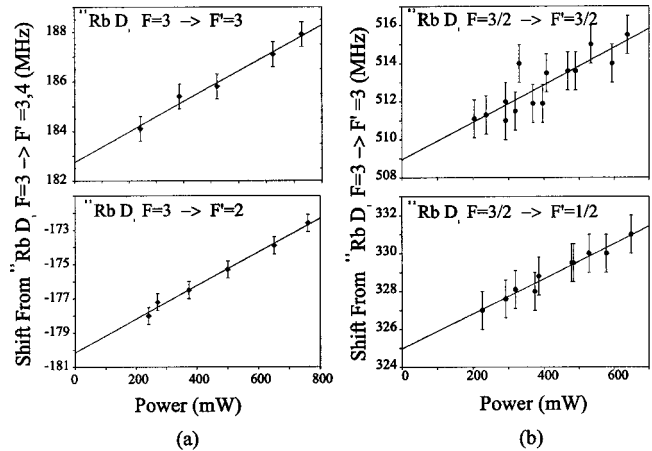


FIG. 3. $D_1$ ($5S_{1/2} \rightarrow 5P_{1/2}$) transition light shifts for (a) the $^{85}$Rb $F=3 \rightarrow F'=3$ and $F=3 \rightarrow F'=2$ transitions and (b) the $^{82}$Rb $F=3/2 \rightarrow F'=3/2$ and $F=3/2 \rightarrow F'=1/2$ transitions as a function of trapping laser power.
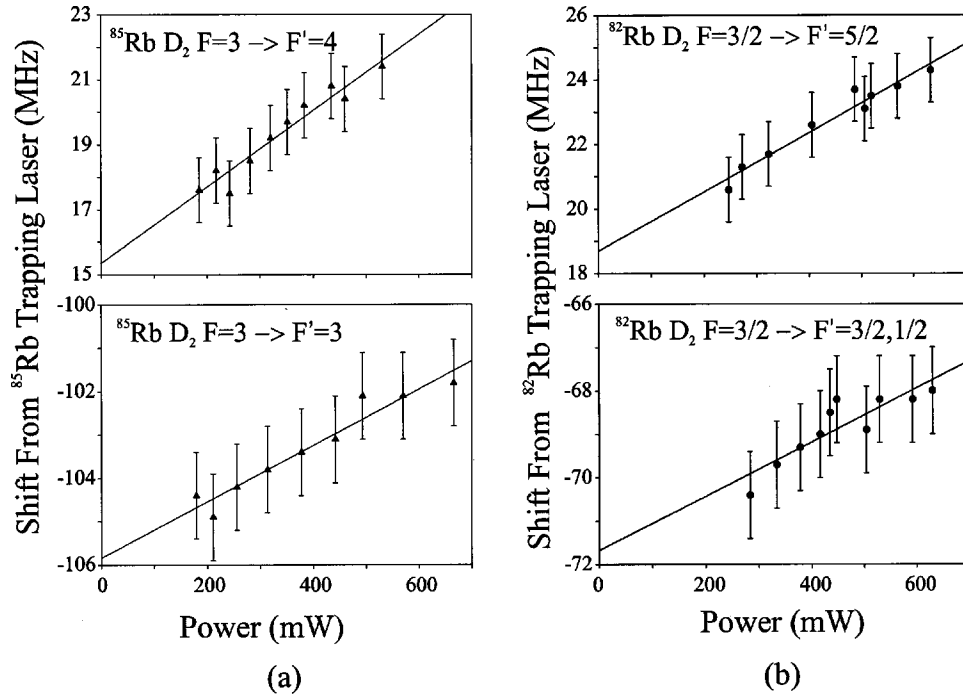
FIG. 4. $5S_{1/2}\rightarrow5P_{3/2}$ $D_2$ transition light shifts for (a) the $^{85}$Rb $F=3\rightarrow F'=4$ and $F=3\rightarrow F'=3$ transitions and (b) the $^{82}$Rb $F=3/2\rightarrow F'=5/2$ and $F=3/2\rightarrow F'=3/2,1/2$ transitions as a function of trapping laser power. The frequency shifts are relative to the fixed frequency of the trapping laser beams used for $^{85}$Rb and $^{82}$Rb, respectively.

over line of $F=3\rightarrow F'=3,2$ $D_1$ transitions. An additional AOM is used to shift the probe beam locking point by 31 MHz, so we can distinguish between the upper EOM sideband resonance with the $F=3\rightarrow F'=3$ transition and the lower EOM sideband resonance with $F=3\rightarrow F'=2$. These two resonance frequencies were measured at different trapping laser power and the results are plotted in Fig. 3(a) where the 31-MHz AOM shift has already been taken into account. The slope of the line yields a light shift averaged over all the Zeeman lines of $\sim0.1$ MHz/(mW/cm$^2$). A linear fit is used to extrapolate the light shift to zero-trapping laser power and yields a $^{85}$Rb $D_1$ transition hyperfine splitting of 362.7(1.5) MHz. The 1.5-MHz error bar, which is typical for our measurements, results from the quadratic sum of statistical uncertainty associated with the extrapolation error of the fit (1 MHz), systematic errors associated with Zeeman shift (1 MHz), and the relative frequency uncertainty of the probe laser (0.5 MHz). Our measured splitting agrees well with previous saturation spectroscopy measurements of 361.5(0.5) MHz [8].

For the $^{82}$Rb $D_1$ line measurement, we locked the probe laser to the $^{85}$Rb $F=3\rightarrow F'=3$ $D_1$ transition and the EOM upper sideband was swept through the $F=3/2\rightarrow F'=1/2$ and $F=3/2\rightarrow F'=3/2$ $D_1$ transitions of the trapped $^{82}$Rb atoms. The data taken with approximately $10^5$ trapped radioactive atoms are plotted in Fig. 3(b). From this data, we derive a hyperfine splitting for the $^{82}$Rb $5P_{1/2}$ state of 184.0(1.5) MHz. The resulting $A$ coefficient is 122.7(1.0) MHz and the isotope shift for the $D_1$ transition is determined to be $\delta\nu^{82-85}=-150.8(2.0)$ MHz. To derive the latter, we used the ground-state hyperfine splitting of $^{82}$Rb from Ref. [4] and the $^{85}$Rb ground state data from Ref. [9]. The $D_2$ line isotope shift was measured previously to be $-153.6(4.4)$ MHz [4].

These isotope shifts indicate that their $J$ dependence (a relativistic effect) is very small.

## C. $D_2$ transition

For the $D_2$ line ($5S_{1/2}\rightarrow5P_{3/2}$) measurement, the probe beam is derived directly from the trapping laser and its frequency shifted using two AOMs. This probe beam is chopped on and off to modulate the trap fluorescence signal. With the exception of the trapping transition (e.g., $F=3\rightarrow F'=4$), the probe beam has a depumping effect on the trapped atoms. To maximize this depump modulation, the repump intensity of the trap is kept to a minimum as before. When probing the trapping transition itself, the probe beam is kept particularly weak ($\sim20$ $\mu$W/cm$^2$) to avoid pushing the atoms out of the zero-magnetic-field region of the trap (the Zeeman shift is $\sim0.5$ MHz/mm in the radial direction). Again, we tested the method on $^{85}$Rb $F=3\rightarrow F'=4$ and $F=3\rightarrow F'=3$ $D_2$ transitions and compared our results with existing saturation spectroscopy results [8]. The data are plotted in Fig. 4(a). From the data, we derive the hyperfine splitting of the $5P_{3/2}$, $F'=4$ and $F'=3$ transitions to be 121.1(1.5) MHz, in good agreement with the saturation spectroscopy results of 121.6(0.5) MHz [8].

The data for the $^{82}$Rb $D_2$ line are plotted in Fig. 4(b). Because we cannot resolve the $F=3/2\rightarrow F'=3/2$ and $F=3/2\rightarrow F'=1/2$ transitions (the splitting between these two hyperfine levels was measured previously to be 0.1 MHz [4]), only an average position for these two states could be determined. The $5P_{3/2}$, $F'=5/2$ and $F'=3/2,1/2$ average hyperfine splitting was measured to be 90.3(1.5) MHz, in good agreement with previous measurement of 89.3(9.0) MHz [4].
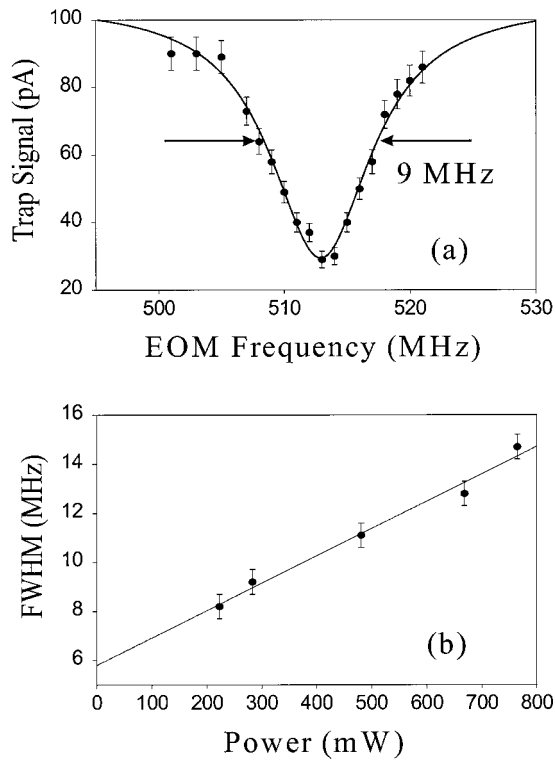
FIG. 5. Line broadening for the $D_1$ transition. (a) Line-shape measurement of the $^{82}$Rb $D_1 F=3/2 \to F'=3/2$ transition (with 300-mW trapping laser power); the solid line is a Lorentzian fit. (b) $^{85}$Rb $D_1 F=3 \to F'=3$ transition linewidth as a function of trapping laser power.

### D. Line broadening

We have also analyzed the line broadening versus trapping laser power used to trap $^{82,85}$Rb atoms. A typical line shape at relatively low trapping laser power is shown in Fig. 5(a) and the linewidth [full width at half maximum (FWHM)] dependence on trapping laser power is shown in Fig. 5(b). There are three effects that contribute to the line broadening in a MOT. One is the radiative broadening of each Zeeman line and the other two effects arise from the fact that each Zeeman line is shifted differently by the light and magnetic field [6,7,10]. Because atoms in a MOT are cold ($\sim 100$ $\mu$K), the Doppler-broadened contribution is negligible ($\sim 0.1$ MHz). At low trapping light intensity, the radiative broadening is linear with trapping light intensity while at higher trapping intensity the light splitting of Zeeman lines dominates. The latter splitting is also linear with the trapping light intensity. These effects have been carefully studied [6,7]. The fact that the extrapolated linewidth at zero trapping laser power yields a $D_1$ transition linewidth of 5.8(0.8) MHz, in good agreement with the $D_1$ natural linewidth of 5.4(0.1) MHz [11], confirms that the trapped atoms are situated at the center (within 1 mm) of the quadrupole magnetic field where the broadening from Zeeman splitting is small.

### IV. SUMMARY

In summary, we have measured the $5P_{1/2}$ hyperfine structure and isotope shift of $^{82}$Rb($t_{1/2}=75$ s) in a magneto-optical trap. We demonstrated that when care is taken to reduce systematic effects, the magneto-optical trapping and probe beam method can provide useful spectroscopic information for a small number of trapped atoms where conventional saturation spectroscopy would be very difficult to carry out. We have determined the $5P_{1/2}$ magnetic dipole coefficient to be $A=122.7(1.0)$ MHz and the $D_1$ transition isotope shift of $\delta\nu^{82-85}=-150.8(2.0)$ MHz. We also measured more precisely the $5P_{3/2}$ hyperfine splitting to be 90.3(1.5) MHz in agreement with the previous measurement of 89.3(9.0) MHz [4]. These results not only enhance our understanding of $^{82}$Rb atomic structure, but also provide useful spectroscopic information that is needed to optically pump and measure the degree of $^{82}$Rb polarization in a pure magnetic trap where a high precision $\beta$-asymmetry experiment is planned.

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